Estuaries and Coasts Vol. 29, No. 6A, p. 979–984 December 2006

Impact and Response of Southwest Florida Mangroves to the 2004 Hurricane Season

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ABSTRACT: Although hurricane disturbance is a natural occurrence in mangrove forests, the effect of widespread human alterations on the resiliency of estuarine habitats is unknown. The resiliency of mangrove forests in southwest Florida to the 2004 hurricane season was evaluated by determining the immediate response of mangroves to a catastrophic hurricane in areas with restricted and unrestricted tidal connections. The landfall of Hurricane Charley, a category 4 storm, left pronounced disturbances to mangrove forests on southwest Florida barrier islands. A significant and negative relationship between canopy loss and distance from the eyewall was observed. While a species-specific response to the hurricane was expected, no significant differences were found among species in the size of severely impacted trees. In the region farthest from the eyewall, increases in canopy density indicated that refoliation and recovery occurred relatively quickly. There were no increases or decreases in canopy density in regions closer to the eyewall where there were complete losses of crown structures. In pre-hurricane surveys, plots located in areas of management concern (i.e., restricted connection) had significantly lower stem diameter at breast height and higher stem densities than plots with unrestricted connection. These differences partially dictated the severity of effect from the hurricane. There were also significantly lower red mangrove (*Rhizophora mangle*) seedling densities in plots with restricted connections. These observations suggest that delays in forest recovery are possible in severely impacted areas if either the delivery of propagules or the production of seedlings is reduced by habitat fragmentation.

Introduction

The response of a community to disturbance depends on several factors: the severity of the disturbance, the species composition, and the size structure of the community. Empirical and theoretical data support the view that more complex communities are more stable (Connell and Slatyer 1977). In diverse, tropical upland forests, a moderate disturbance is predicted to have little effect on community structure because of the diverse understory (Everham and Brokaw 1996). The complexity of the understory largely reflects the complexity of the canopy. Seedlings and saplings in canopy gaps will grow to reestablish the canopy. Given the species-poor nature of southwest Florida mangrove forests (i.e., generally only 3 species) and the lack of a seedbank, these forests are thought to be less stable (Baldwin et al. 2001). It is important to follow the immediate and long-term response of mangroves to hurricanes in order to detect whether recovery will be affected by human activities, such as forest fragmentation.

The degree of disturbance is thought to determine the pathway for regeneration after a catastrophic disturbance. Canopy losses, as the result of lightning strikes, are presumed to be temporary (Smith et al. 1994; Imbert et al. 2000; Sherman et al. 2000) and do not result in significant shifts in mangrove forest community composition. The small size of the canopy gap allows for recolonization from propagules produced in the nearby, intact canopy. Moderate and severe disturbances, such as hurricanes, can result in significant shifts in community composition (Baldwin et al. 2001), if canopy reproduction is reduced (Proffitt unpublished data; Milbrandt unpublished data) or if the delivery of propagules is inhibited by habitat fragmentation (Lewis 2005). When canopy losses are widespread, mangroves partly depend on recolonization from intact, reproducing forests, which may not be geographically close. It is unknown whether anthropogenic fragmentation (e.g., roads, ditches, diversion) will impair the immediate response or the resiliency of mangroves to a catastrophic hurricane.

Minimum pressure associated with the category 4 Hurricane Charley was recorded on 13 August 2004, at approximately 1545 EDT at a central location on Sanibel Island approximately 18 to 20 km from the hurricane eyewall. A sharp gradient in barometric pressure across the storm resulted in hurricane-force winds and subsequent losses of mangrove canopy. The availability of data on forest structure collected 4 mo preceding the storm provided

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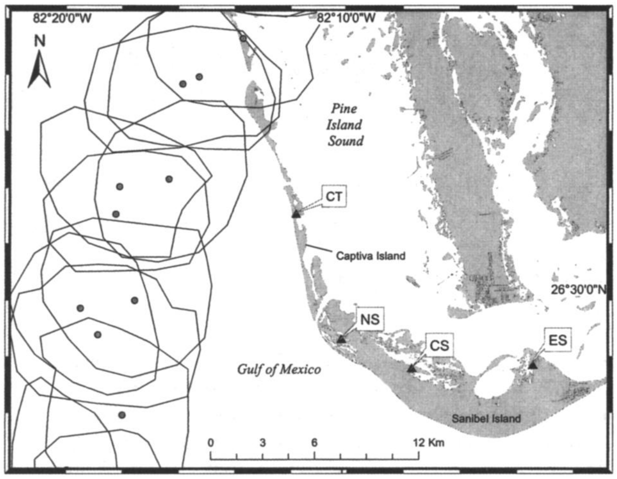

Fig. 1. Map of the study sites, including mangrove study sites and the approximate track of Hurricane Charley. Dots indicate the center positions of the storm, surrounded by circles that are the approximate circumference of the eyewall.

a unique opportunity to examine whether the plots chosen for a management concern (e.g., impoundment) responded differently than plots with an unrestricted connection to open water. The study locations were located on a north-south orientation on two barrier islands; the closest site to the eyewall was less than 4 km distant, while the farthest was 19 km distant. Canopy loss, mangrove forest structure, mangrove species composition, and seedling densities were compared along the gradient of disturbance created by the track and catastrophic winds associated with Hurricane Charley.

Materials and Methods

Study Sites

Permanent plots (24) were established on two barrier islands, Sanibel and Captiva, in the Charlotte Harbor region of southwest Florida. Plots were established in April 2004 in 8 locations. The locations were situated in 4 regions of the Sanibel and Captiva barrier islands; East Sanibel (ES), Central Sanibel (CS), Northwest Sanibel (NS), and Captiva (CT; Fig. 1). In each of the 4 regions, 3 plots were established in an area because of a management concern (e.g., impoundment), while 3 plots were established in an adjacent area with an open connection to the estuary. In each plot, the location of the center point of each plot was determined by pacing out a random distance along a random bearing from an initial location. Random numbers were generated within a spreadsheet using a random number function. The center of each circular plot (113 m^2) was marked with a 3-cm diameter PVC stake and the perimeter of the plot was marked with flagging tape and spray paint (Smith 2000; Worley 2005).

Pre-hurricane Methods

Data on the following three species were collected: red mangrove (*Rhizophora mangle*), white mangrove (*Laguncularia racemosa*), and black mangrove (*Avicennia germinans*; Craighead 1971). The diameter at breast height (DBH) of tree stems ($\geq$ 1 cm DBH) was measured. The total number of stems measured in each plot varied, depending on the location and age of the forest stand; the average number of stems plot^{-1} was 49. Seedling height (DBH $<$ 1 cm, but height $>$ 30 cm), was measured vertically from the base of the mangrove to the bottom of the terminal bud. The terminal bud was not included in the seedling height because of variation in the bud size owing to differences in development. Seedlings less than 30 cm in height were not recorded because it was not clear whether these seedlings had established. Canopy density (% cover) was measured in the center of each plot using a spherical densiometer (Strickler 1959) by facing the four directions of the compass and averaging the four cover measurements.

Post-hurricane Methods

Following landfall of Hurricane Charley, forest data were collected using the same methods prior to the hurricane. A classification scheme also was devised to categorize each stem based on its damage (Roth 1992; Smith et al. 1994). Each stem was assigned to one of three damage classes; severely impacted, impacted, or non-impacted. Uprooted stems and stems snapped below the crown were considered severely impacted; stems with noticeable branch loss were categorized as impacted. Non-impacted trees were those stems that appeared to be structurally sound, that is, without damage to the branch structure. Canopy density was measured post-hurricane in October 2004, November 2004, January 2005, and April 2005.

The distance from the four regions to the hurricane eyewall was estimated using ArcGIS based on data derived from satellite imagery. The storm track and eyewall location were calculated by the Southwest Florida Regional Planning Council's GIS.

Statistical Analysis

All data were tested for normality using a one-way, Kolmogorov-Smirnov Test. Data were also tested for homogeneity of variance with a Levene test. In cases where data were not normal or heteroscadastic, the data were transformed logarithmically ($\log_{10}$). In cases where data were not normalized by transformation, nonparametric statistics were used.

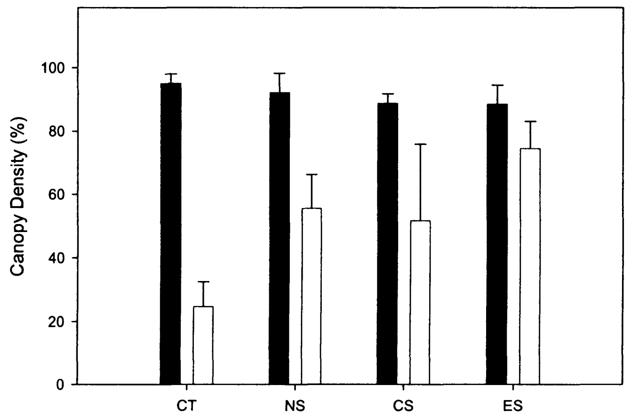

Fig. 2. Canopy density (%) on southwest Florida barrier islands before and after Hurricane Charley.

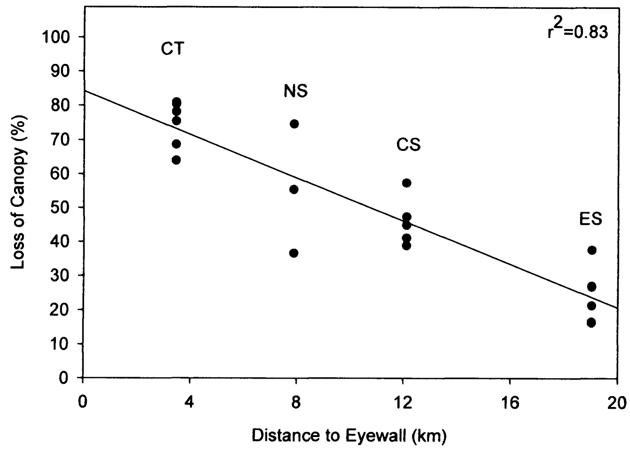

Fig. 3. Relationship between the change in canopy density and the distance to the hurricane eyewall.

Statistical tests were performed with SAS 9.0; the significance level for all statistical tests was set at $p < 0.05$.

Six plots in each region were grouped after no significant differences were found in canopy density between areas with an open connection and areas with a restricted connection (Kruskal-Wallis test, $p = 0.10$). A Wilcoxon Signed Ranks Test was used to test the differences in canopy density before April 2004 and after the landfall of Hurricane Charley (September 2004). Multiple Mann-Whitney U-tests were used to determine if the 4 regions had significantly different canopy densities after the disturbance (Scheiner and Gurevitch 2001). A Pearson product-moment correlation analysis was used to determine the relationship between change in canopy density and distance to the hurricane eyewall.

DBH data were logarithm transformed ($\log_{10}$). A Kruskal-Wallis test was used to determine significant differences in log DBH among damage classes (i.e., severely impacted, impacted, and non-impacted). Each of the three mangrove species was tested independently. Mortality of trees < 5 cm in diameter was compared to mortality of trees > 5 cm to compare the effects of Hurricane Charley to other reports of hurricane disturbance (Smith et al. 1994). The percentage of severely damaged stems in restricted plots was compared to unrestricted plots by calculating the proportion of severely damaged stems to the total number of classified stems. Data from the NS region were not included because the plots in the areas of management concern experienced a significant mangrove die-off in 2001.

Descriptive statistics and a Wilcoxon rank-sum, nonparametric test were applied to determine the differences in stem density, seedling densities, and stem size between restricted and unrestricted plots.

Results

Canopy density was significantly lower at all four regions following the hurricane (Fig. 2). The decrease in canopy density was greatest at the CT region, closest to the estimated storm track (Fig. 1). The least change in canopy density was recorded at the ES site, farthest from the storm track. There was a significant and negative correlation between the change in pre-canopy and post-canopy cover and distance from the eye wall (Fig. 3).

Species-specific differences were not observed in response to hurricane disturbance. There were no significant differences among mangrove species in the degree of effect they experienced from the storm. The size of severely impacted trees and impacted trees was significantly greater than non-impacted trees of all species (Fig. 4). Trees > 5 cm DBH had a 47% initial mortality, while trees < 5 cm DBH had a 20% initial mortality.

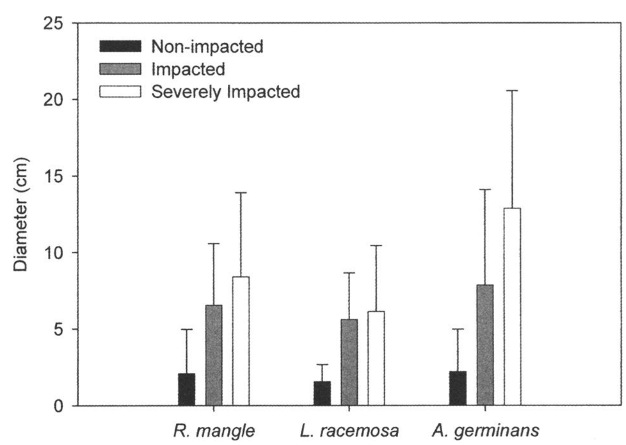

Fig. 4. Tree size (diameter at breast height) relative to damage category experienced by mangrove species.

TABLE 1. Percentage of severely damaged stems in East Sanibel and Central Sanibel.

Connectivity	*Avicennia germinans*	*Laguncularia racemosa*	*Rhizophora mangle*
Restricted	7	27	3
Open	55	50	37

Prior to the landfall of Hurricane Charley, stem density and stem size for each species were compared in plots with restricted connections versus open connections. In the ES region there were significantly smaller DBH and greater stem densities of *R. mangle* and *L. racemosa* in restricted plots. There were significantly smaller DBH and greater stem densities of *R. mangle* in restricted plots of the CS region, but DBH for *L. racemosa* was significantly larger and stem densities were greater in the CS region. In the CT region, plots with restricted connections had significantly greater *A. germinans* stem diameters. In a post-hurricane analysis, the percentages of severely damaged trees were lower in areas with restricted connections to open water in CS and ES (Table 1). While in the CT region, the percentage of severely impacted *A. germinans* stems was higher in the restricted plots (88%) versus open plots (63%).

Post-hurricane densities of *R. mangle* seedlings were observed to be significantly lower in plots with restricted connections (Table 2). Densities of *A. germinans* and *L. racemosa* seedlings were not different between restricted and unrestricted plots. The mean density of *R. mangle* seedlings in CS was 4.3 seedlings m^{-2}, while in ES the mean *R. mangle* seedling density was 4.0 seedlings m^{-2} (Fig. 5). Mean density of *R. mangle* seedlings in CT and NS was $< 1\ m^{-2}$.

Recovery of the canopy revealed slow, if any, recovery toward pre-disturbance levels, as evidenced by measures of canopy density in the months after the storm. The only area with a positive trend toward recovery within the study area was ES, the most distant from the eyewall. The trend, however, was not statistically different from zero ($r^2 = 0.01$).

Discussion

Hurricane effects have often been evaluated through post-disturbance reconstruction, where it was possible to determine the timing of the death of downed trees (Roth 1992; Smith et al. 1994; Doyle et al. 1995; McCoy et al. 1996; Imbert et al. 2000). We report the first evaluation of immediate effects from a hurricane using mangrove structure data collected before the hurricane made landfall. While it is tempting to study only the most severely affected sites when a hurricane occurs, the establishment of field plots prior to the hurricane eliminated a preference for severely disturbed sites. A gradient of hurricane disturbance, as evidenced from pre-disturbance and post-disturbance surveys of canopy density, provided the framework examining the relationship between the hurricane disturbance and resulting effect to pristine and human-altered mangrove forests.

TABLE 2. Post-hurricane *Rhizophora mangle* seedling density in areas with restricted versus open tidal connections.

	Region			
Connectivity	East Sanibel	Central Sanibel	North Sanibel	Captiva
Restricted	0.9	0.5	0.0	0.1
Open	4.0	4.3	0.3	0.6

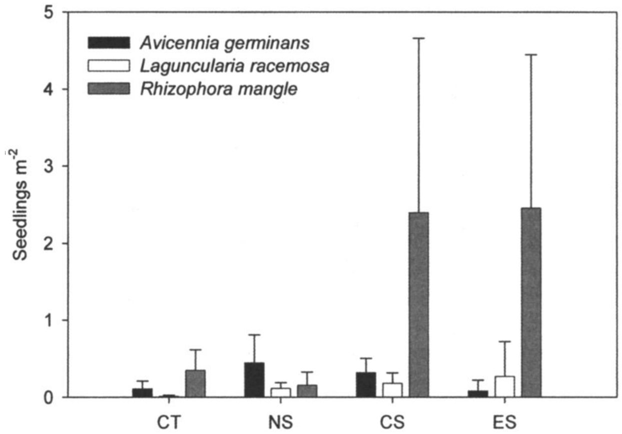

Fig. 5. Mangrove seedling densities recorded at the four study sites. Abbreviations are as follows: CT = Captiva, NS = Northwest Sanibel, CS = Central Sanibel, and ES = East Sanibel.

Doyle et al. (1995) concluded that defoliation and branch losses (expressed as canopy density) decreased exponentially with increasing distance from the storm track. A closer inspection of the data offered by (Doyle et al. 1995) indicated that this relationship was linear within close proximity (0–40 km) of the eyewall. Our data revealed a significant and negative relationship between changes in canopy density and distance to the eyewall. The most severe damage was limited to those areas within 4–12 km of the storm's eyewall. Severe damage was confined to a generally small region because of the relatively small diameter of Hurricane Charley's eyewall (16–24 km diameter, National Oceanic Atmospheric Administration). In comparison, Hurricane Katrina, also a category 4 storm, had an eyewall diameter of 48 km.

The severity of the damage was a function of forest-size structure. Tree size was the primary factor distinguishing the severely impacted from the non-impacted groups. Smith et al. (1994) concluded that trees < 5 cm in diameter had less than 10% initial mortality after Hurricane Andrew; while a 20% initial mortality of trees < 5 cm in diameter is reported here. Several other studies have demonstrated that larger trees are more likely to suffer stem breakage or toppling in the path of a hurricane (Roth 1992; Smith et al. 1994; McCoy et al. 1996; Baldwin et al. 2001). While others have suggested that *L. racemosa* is more sensitive to disturbance (e.g., Doyle et al. 1995; McCoy et al. 1996), there was no evidence for greater susceptibility of mortality in our observations.

There were lower percentages of severely damaged stems in plots with restricted tidal connections. In areas closer to the eyewall, a majority of the stems were severely impacted regardless of the connectivity. It would appear that the effect is primarily attributable to the distance to the eyewall and secondarily related forest size structure. Changes in forest-size structure due to human activities may have indirectly contributed to the severity of effect from hurricane disturbance, but it was not possible to determine whether the changes were caused by human activities.

Recovery of the canopy depended partly on the severity of disturbance, where mangroves close to the eyewall lost most, if not all, of their canopy structure. Complete crown loss was not compensated for in CT during the 8 mo after the hurricane as evidenced by a negative relationship in canopy density in the time after the hurricane made landfall. In lightly disturbed areas (i.e., ES), there were slight increases in canopy density over time. These observations indicated that recovery in ES was likely the result of refoliation of the intact branch structure. In mangrove forests, there is a species-specific ability to regrow a new canopy from epicormic sprouts (Tomlinson 1986). *A. germinans* and *L. racemosa* have the ability to regrow, while *R. mangle* lose this ability as they grow larger.

In post-hurricane surveys, there were lower densities of *R. mangle* seedlings observed in regions closer to the eyewall. We also observed lower densities of *R. mangle* seedlings in areas with restricted connections. These observations were made after the hurricane; a similar trend was evident in pre-hurricane surveys (Milbrandt unpublished data). Consistently lower densities of *R. mangle* seedlings in impounded areas suggest that human activities are either decreasing seedling production or affecting propagule movement. Plots with restricted connections to open water may experience delays in recolonization if the delivery of propagules is reduced because of increased habitat fragmentation. Species composition and the rate of colonization partially depend on the delivery of propagules from adjacent forests and the capture of those propagules by woody debris (Krauss et al. 2005). While there are reports of complete inhibition of seedling recruitment and understory growth associated with changes in geomorphology (Cahoon et al. 2004), inhibition of propagule movement and seedling production as a result of habitat fragmentation are not well understood.

Although hurricane disturbance is a natural occurrence to mangrove forests, the effect of human alterations on the resiliency of the estuary is unknown. Modifications to hydrology (e.g., road construction) and connectivity have contributed to changes in the size structure and composition of mangrove forests. While it appears that the immediate response to hurricane disturbance in areas affected by human activities was minimal, there is the possibility that mangroves will experience a delayed recovery. The delivery of propagules and the productivity of seedlings may be limited where mangrove habitats are fragmented. Should low seedling densities persist in fragmented areas for subsequent years, restoration of tidally restricted areas may be necessary.

ACKNOWLEDGMENTS

Tim Walker Southwest Florida Regional Planning Council (SWFRPC) provided the track of Hurricane Charley, which was used to calculate distances from the eyewall to the study sites. The following research assistants helped to collect, enter, and check data: Megan Tinsley, Justin Spinelli, Brad Klement, A. J. Martignette, and Maggie May. Mike Hannan reviewed and improved earlier versions of the manuscript. Funding was provided by Sanibel-Captiva Conservation Core Research Fund and the City of Sanibel. Access to study sites was provided by the J. N. "Ding" Darling National Wildlife Refuge.

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Source of Unpublished Materials

Proffitt, C. E. unpublished data. Florida Atlantic University, 777 Glades Road, P. O. Box 3091, Boca Raton, Florida 33431-0991

Received, December 14, 2005
Revised, April 19, 2006
Accepted, June 4, 2006